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Beam Loss Scenarios for MuCool Test Area*

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Abstract
The MuCool Test Area (MTA) is an intense primary beam facility derived directly from the Fermilab Linac to to test heat deposition and other technical concerns associated with the liquid hydrogen targets, gas-filled rf cavities, and other apparatus being developed to cool intense, large-emittance muon beams. In this study the results of Monte Carlo modeling of several beam loss scenarios are presented.

1 Introduction

The MTA facility was designed to test targets and other muon cooling apparatus using the intense Fermilab Linac beam. The requested intensity of the proton beam for the MTA is essentially full Linac capability, or 1.6×10^{13} protons per pulse and an energy of 400 MeV. Two modes of operation will be supported in the MuCOOL beamline: one mode for emittance measurements (and beamline studies) and a second mode for MTA experiments. Maximum beam intensity for these two modes is: 9.6×10^{15} protons/hr – 600 beam pulses/hour of full Linac beam pulse intensity (1.6×10^{13} protons/pulse) to the emittance beam absorber and 9.6×10^{14} protons/hour – 60 beam pulses/hour of full Linac beam pulse intensity to experiments in the MTA experimental hall.

This extremely high intensity implies careful investigation into and application of proper shielding materials and configuration in order to satisfy the following two requirements: (i) to reduce the instantaneous dose rate outside of the experimental enclosure to prescribed levels appropriate for the area considered; (ii) to ensure the civil construction of the hall is capable of additional shielding and, further, that the weight of the shielding is commensurate with the loading specifications of the enclosure, notably the ceiling. A number of scenarios for beam loss at different locations were studied in order to determine the maximum beam intensity which is in compliance with the existing shielding. The modeling was performed with the MARS15 code [1].

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2 Beam Loss Scenarios

In this study we focus on beam losses that could lead to a potentially dangerous radiation outflow through existing penetrations. The worst-case loss scenarios studied from upstream to downstream for the following penetrations include:

- Hatch shield wall penetrations;
- ceiling hydrogen vent;
- penetrations between the MTA experimental hall and gas shed;
- horizontal penetrations between the MTA experimental hall and the refrigerator room in the service building;

Fragments of the geometry model as shown use the following color scheme to denote materials: white, light blue, green and grey colors correspond to vacuum, air, soil and regular concrete, respectively. The meaning of the other colors can vary depending on materials used in the system under consideration. It should be taken into account also that boundaries between different regions are shown with black lines. When the resolution of the figure is inadequate, small regions sometimes are not distinguishable and appear as black regions.

2.1 Hatch shield-wall penetrations

Three penetrations were established in the shield wall to accommodate two RF waveguides and one containing cables from the RF trench at the top of the berm into the beamline stub and eventually the experimental hall. The cabling is tightly packed with sandbags to eliminate any potential for prompt dose. The worst case loss scenario for the two RF penetrations was determined to be approximately 7’ downstream of the shield wall. Figure 1 presents the MARS model and the results for a beam loss on a quadrupole at this location. The prompt dose at the exit of the coaxial penetration is determined to be 1.15×10^{-3} mrem/pulse. Conservatively doubling this number to cover both penetrations gives 1.38 mrem/hr for emittance mode and 0.138 mrem/hr for the experiment mode.

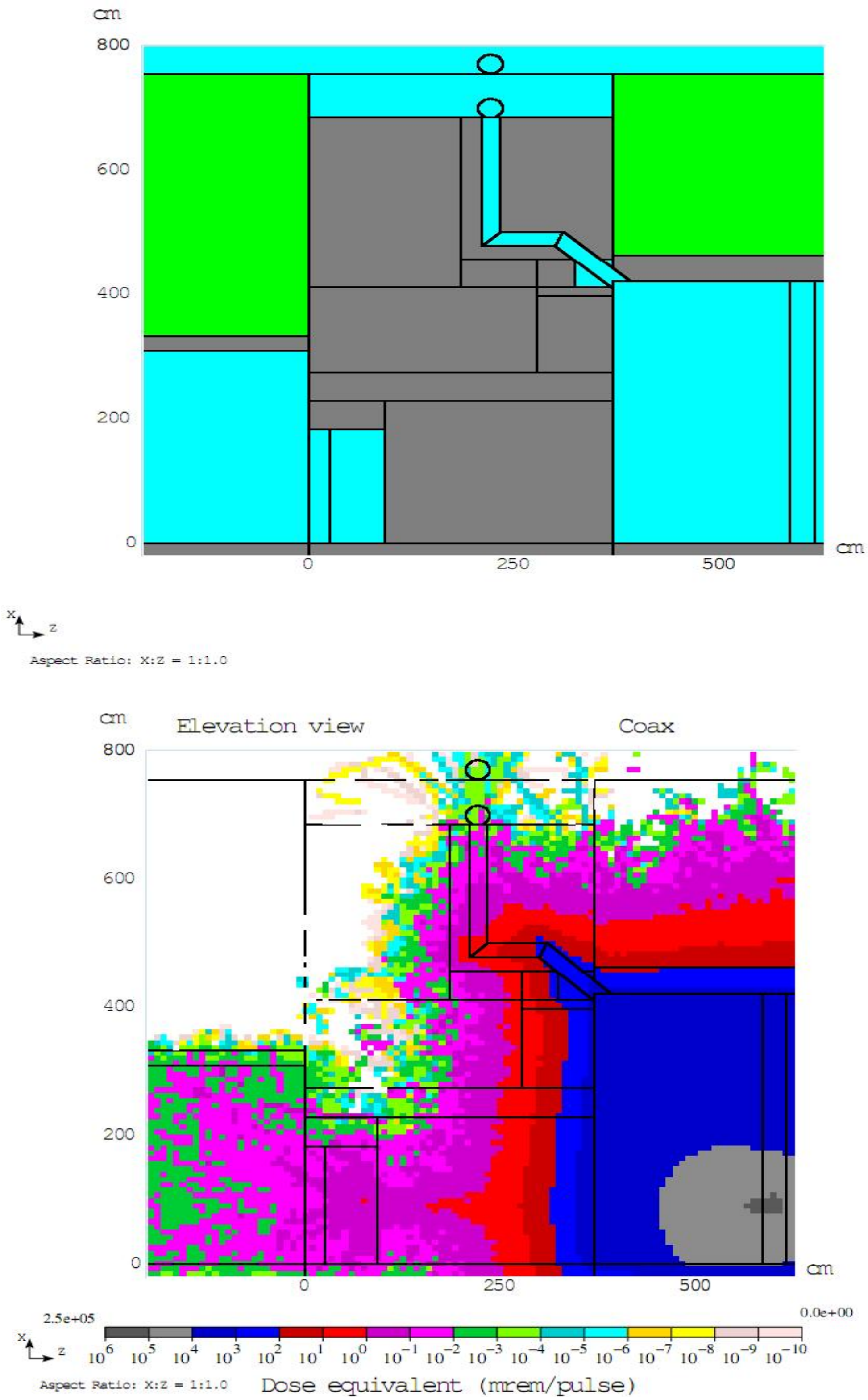


Figure 1. A cross section (top) of the MARS model of the shield wall showing the vertical coaxial RF wave guide penetration. The prompt dose (bottom) is shown from a beam loss on a quadrupole (10″ of steel) located 7′ downstream of the wall.

2.2 Ceiling vent for hydrogen

A 20” diameter penetration in the experimental hall ceiling provides a vent for gases to the top of the berm. This vertical vent is located in the upstream part of the MTA target hall.

Emittance Mode

The worst-case loss scenario for the emittance mode is where beam is deposited entirely on the emittance absorber which is the location closest to the ceiling vent for this mode of operation. The emittance absorber is a 6" dia. and 26" long cylinder with the upstream part an 8" length of copper and the downstream part steel (Figure 2, top, left). Although the calculations are for repetition rate of 1 Hz, the results can be easily scaled to 0.167 Hz for the emittance mode (Figure 3, left). Detailed MARS simulations were performed also for a 2nd case: a smaller 1” diameter emittance absorber for comparison (Figure 3, right). The present emittance absorber produced the maximum prompt dose at the exit of the ceiling vent of less than 0.1 mrem/pulse or 60 mrem/hr.

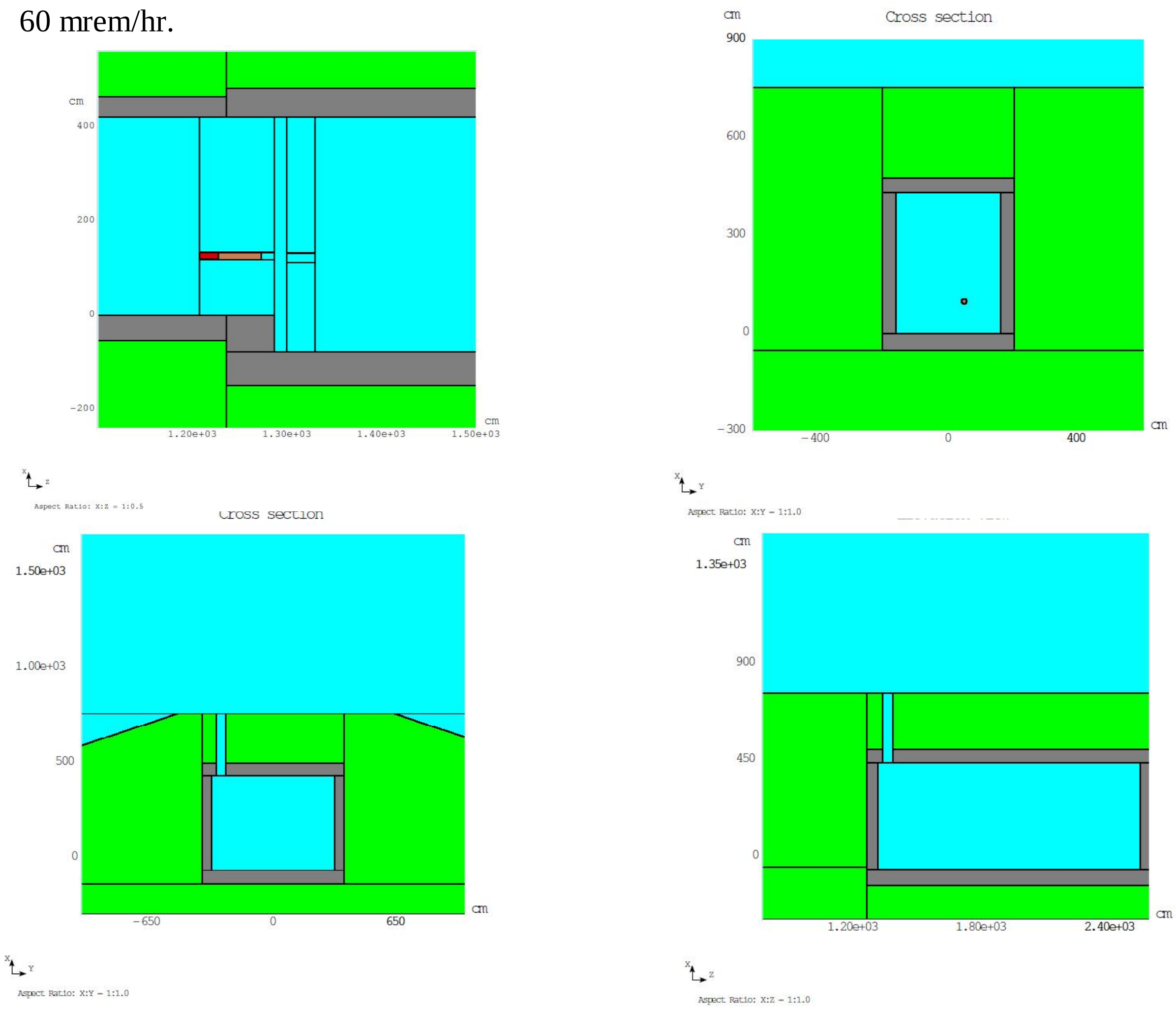


Figure 2. The MARS model of the emittance absorber, ceiling vent and enclosure looking downstream showing location of beamline (top left), and transverse (top right and bottom left) and longitudinal (bottom right) cross sections of the vent and MTA experimental hall.

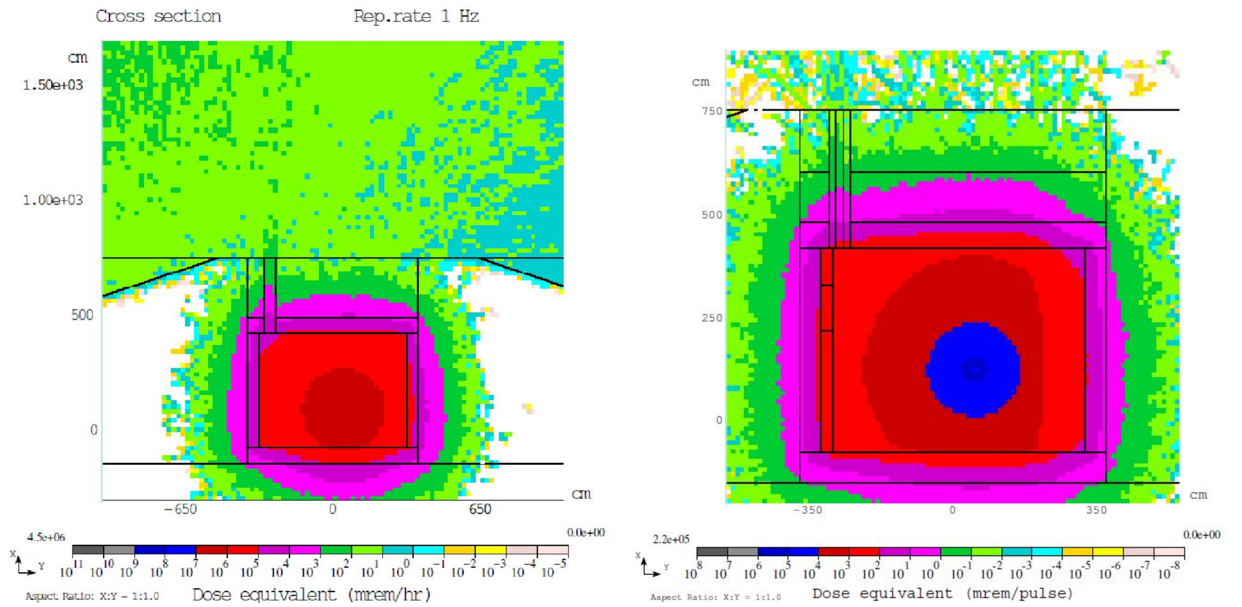


Figure 3. The MARS results for the ceiling vent for the 6" diameter emittance absorber (left) and a smaller 1" diameter version (right).

Experiment Mode

The worst case beam loss scenario for the ceiling vent assumes that the beam hits a 30-cm steel target located in the beam line as close to the vent as possible (see Fig. 4). The calculated dose distributions around the vents are shown in Fig. 5. One can see that there is some radiation streaming upward in the biggest vent and an estimated dose rate atop the shielding (X=750 cm) is about 0.3 mrem/pulse. At the same time, radiation streaming through the smaller vents is negligible.

Neutron energy spectrum was calculated in the upper part of the 50-cm penetration for the case when there are no polyethylene beads inside the penetration (see Fig. 6). A numerical representation of the spectrum is given in Table 1.

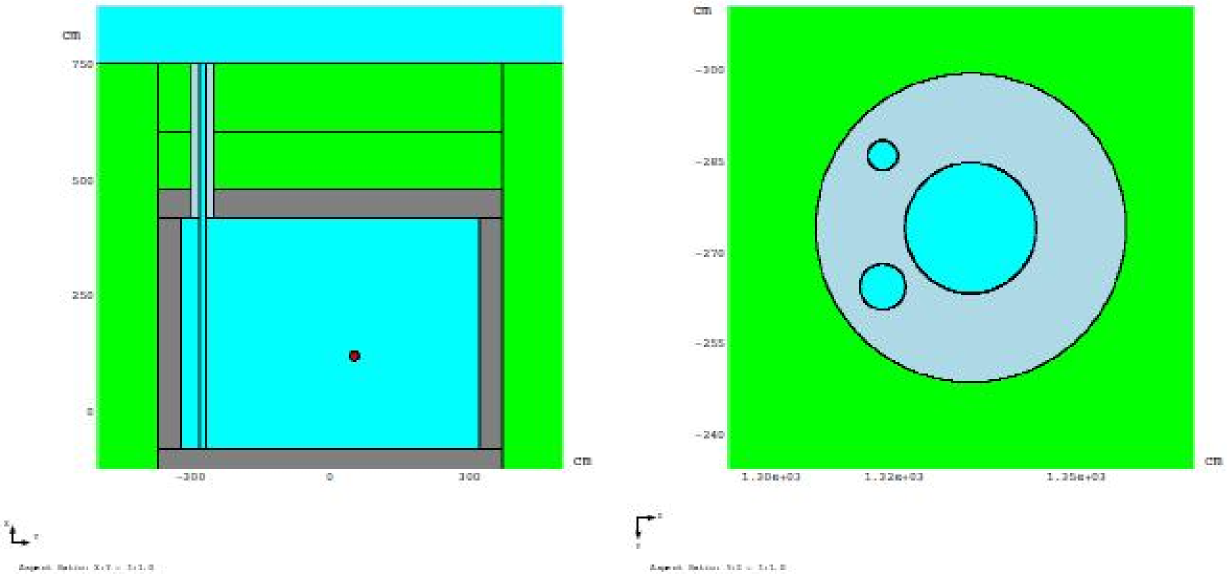


Figure 4. A cross section (left) of the MARS model of the MTA target hall showing the vertical ceiling vent and the location of the beam loss (in the beamline) looking downstream. The penetration which contains the steel vent for hydrogen is 50 cm in diameter and the vent itself is 21.5 in diameter. The volume inside the penetration but outside the vent is filled with polyethylene beads shown in turquoise color (right). Also shown are two smaller vents (5 and 7.5 cm in diameter.

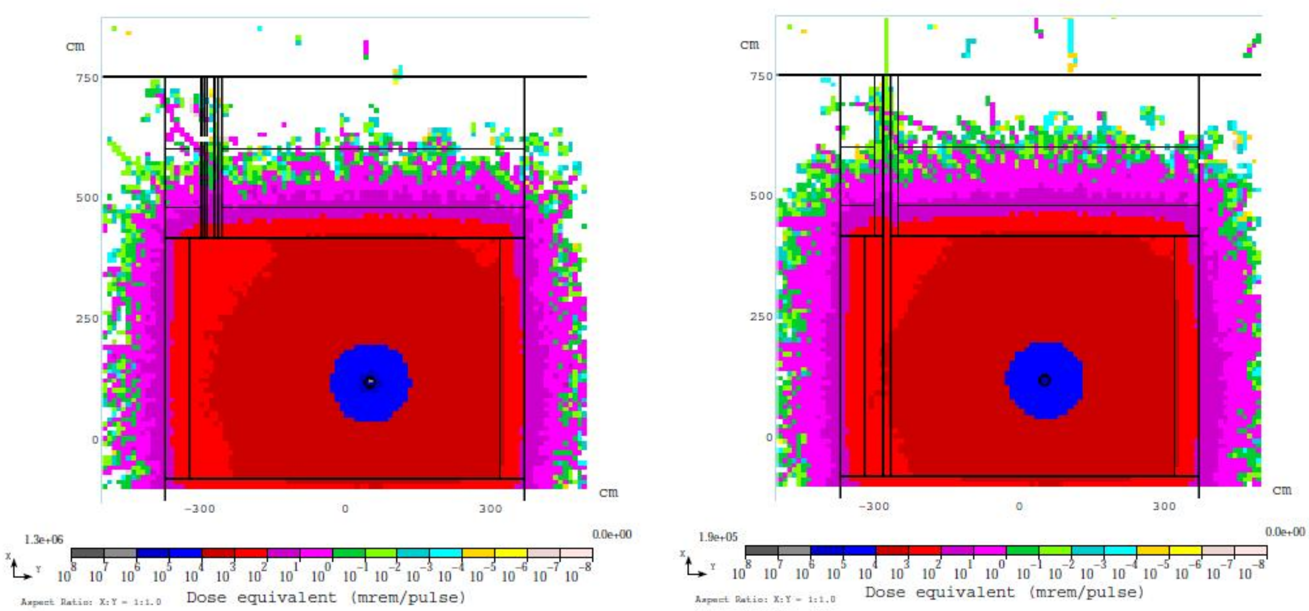


Figure 5. The calculated dose distribution for the three vents: a cross section through the 21.5-cm vent (left) and through the two smaller vents (right).

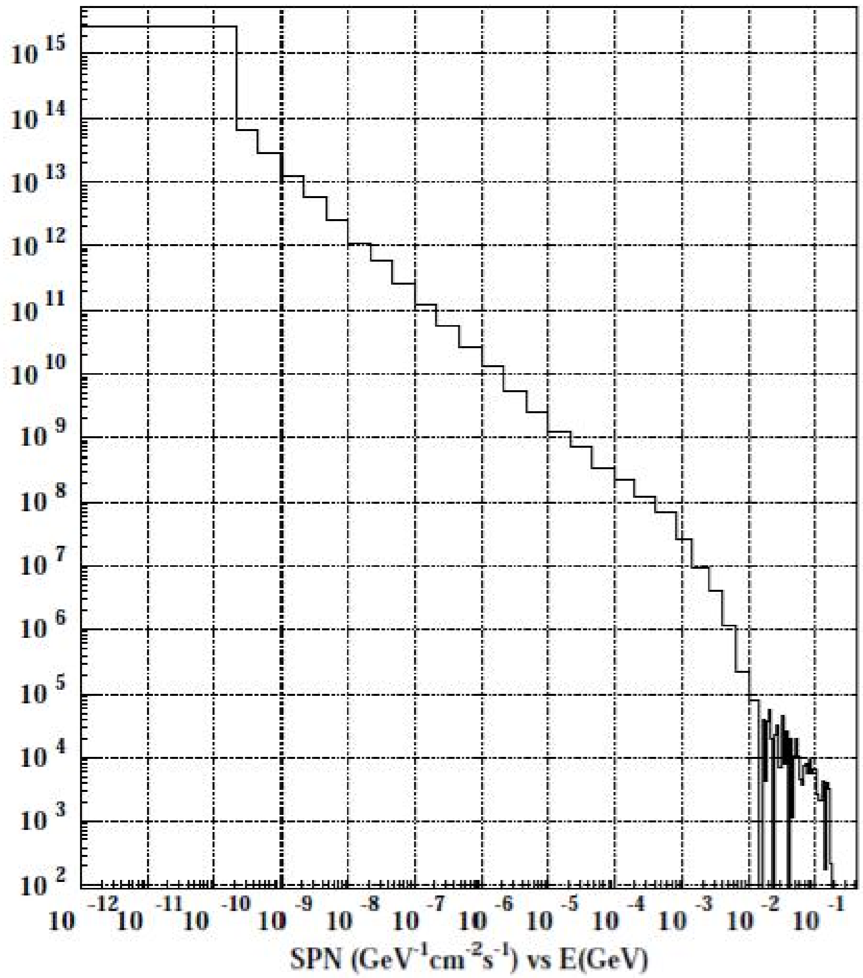


Figure 6: The calculated neutron energy spectrum in the upper part of the 50-cm penetration without the polybeads.

Table 1: The calculated neutron energy spectrum in the upper part of the 50-cm penetration without polybeads.

Energy range (eV)	Neutron fraction (%)
0-1	63.4
1-10	4.6
10-100	4.6
100-1000	4.6
$10^3 - 10^4$	4.6
$10^4 - 10^5$	5.5
$10^5 - 10^6$	8.7
$10^6 - 10^7$	3.9
$10^7 - 10^8$	0.1

2.3 Penetrations to the gas shed

There are three, single-leg penetrations between the MTA target hall and the gas shed (see Fig. 7). The three penetrations to the gas manifold room are filled with polyethylene beads and cabling except for two 0.25” copper lines that feed gas to the experimental hall.

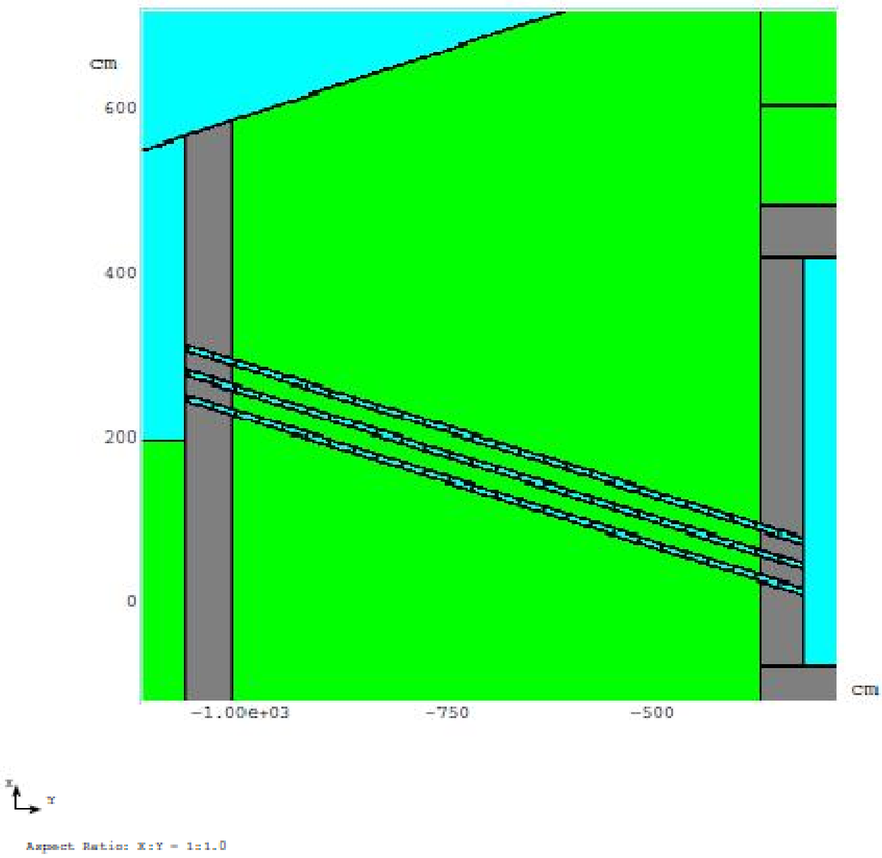


Figure 7: A cross section of the MARS model with the penetrations between the MTA target hall and gas shed.

In the worst case beam loss scenario, the beam hits a 30-cm steel component or target located in the beam line as close to the penetrations as possible. The calculated dose rate at the entrance to the central penetration is 1.68×10^{3} mrem/pulse. One has a reliable estimate of the dose attenuation in the penetration only up to 4 m in depth. The estimated dose attenuation in the penetration at 4 m is 3×10^{-7} and 5×10^{-5} with and without polyethylene beads, respectively, in the penetration (Figure 8). Therefore, corresponding dose rates are 0.0005 and 0.084 mrem/pulse. The calculated neutron spectra in the penetration are given in Fig. 9.

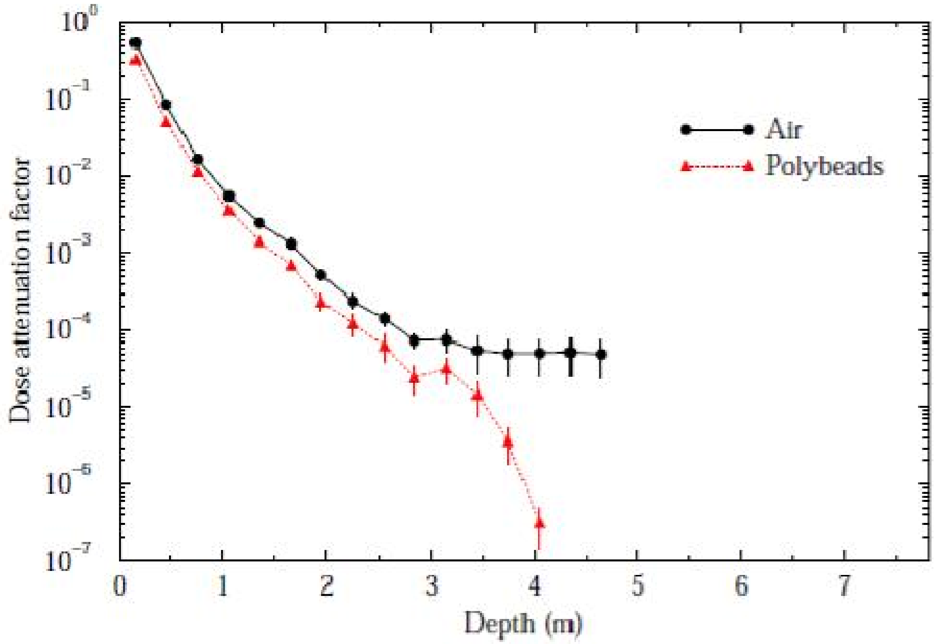


Figure 8: The calculated dose attenuation in the central penetration with and without polyethylene beads inside.

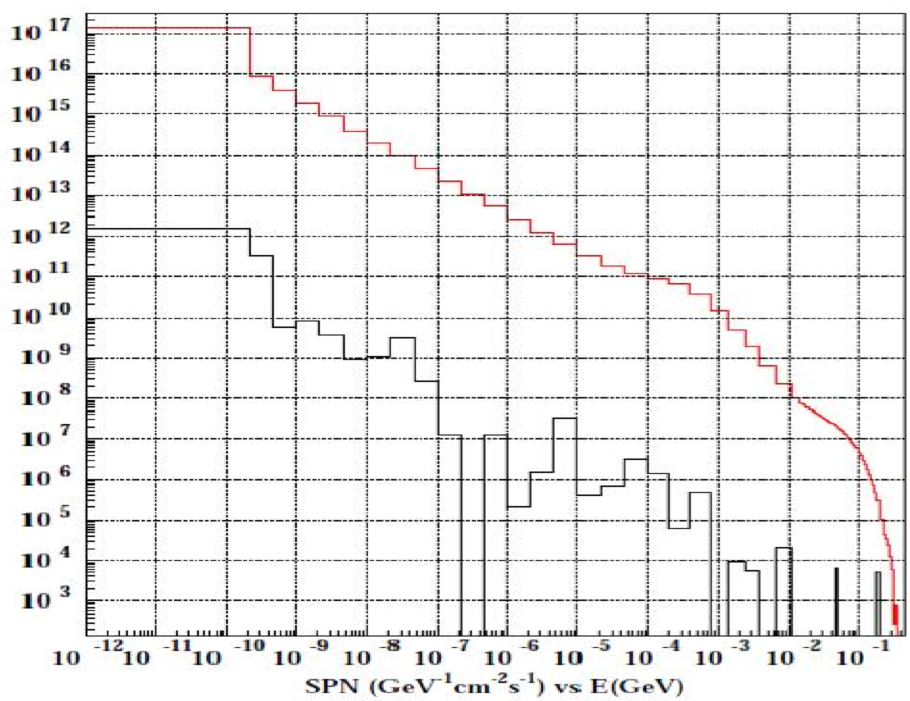


Figure 9: The calculated neutron energy spectra in the central penetration to the gas shed with the penetration filled with air: entrance to the penetration in the target hall (red) and midpoint (black). The normalization is arbitrary.

2.1 Horizontal penetrations to the refrigerator room

Six straight penetrations, one 10", one 8", and four 4" diameter openings, run from the experimental hall to the refrigerator room, Figures 10 and 11. The penetrations themselves and their contents are detailed in Reference 3.

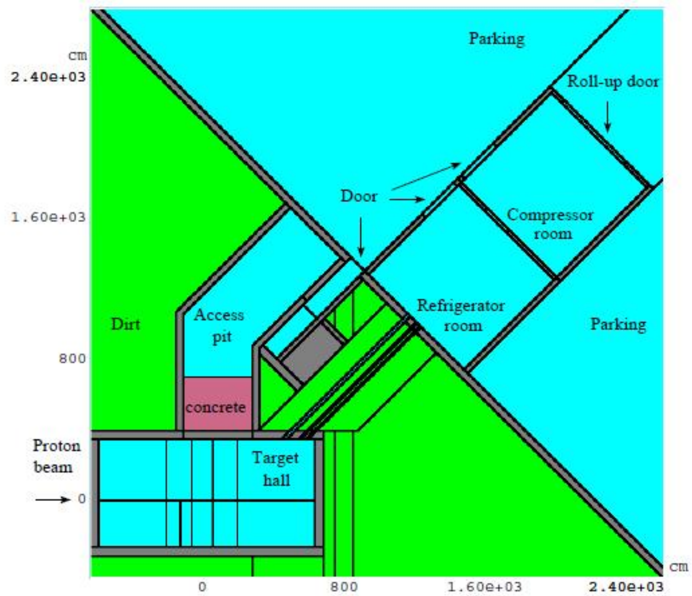


Figure 10: A plan view of the MARS model of the MTA at upper level.

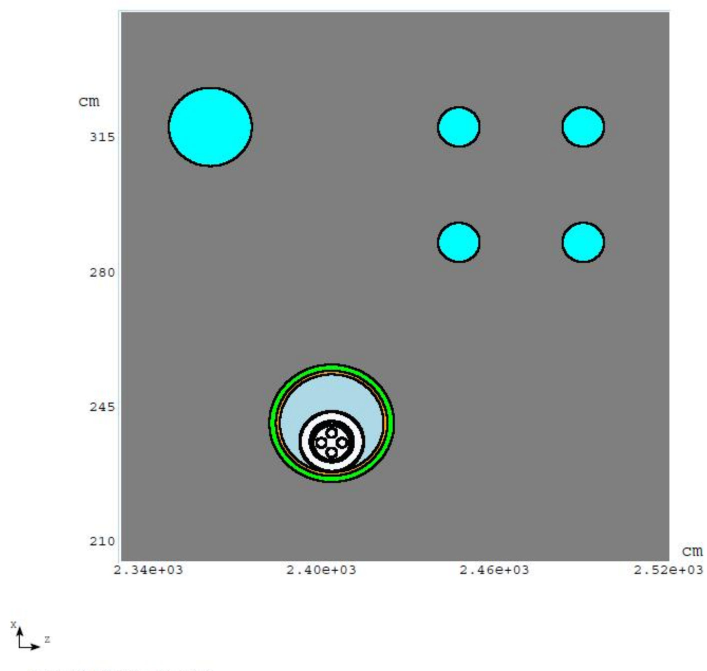


Figure 11: A cross-sectional view of the model showing all six penetrations and the cryogenic channel which resides in the largest, 10" penetration. The volume inside the 10" pipe (outlined in brown) but outside of the cryogenic channel is filled with polyethylene beads (shown in turquoise). Cables and pipes that exist in the five smaller penetrations, the 8" and four 4" penetrations, are ignored in the model and assumed filled with air.

The largest penetration is 10” in diameter, the second 8” in diameter, and the four penetrations are each 4” in diameter. In the MTA experimental hall there is no shielding shadowing the penetrations. In order to predict dose rate in the service building and at parking lot, two beam loss scenarios were studied (see Fig. 12): a) beam loss on a thick target (100% interaction length) in the experimental hall, and (b) beam deposited on the emittance absorber.

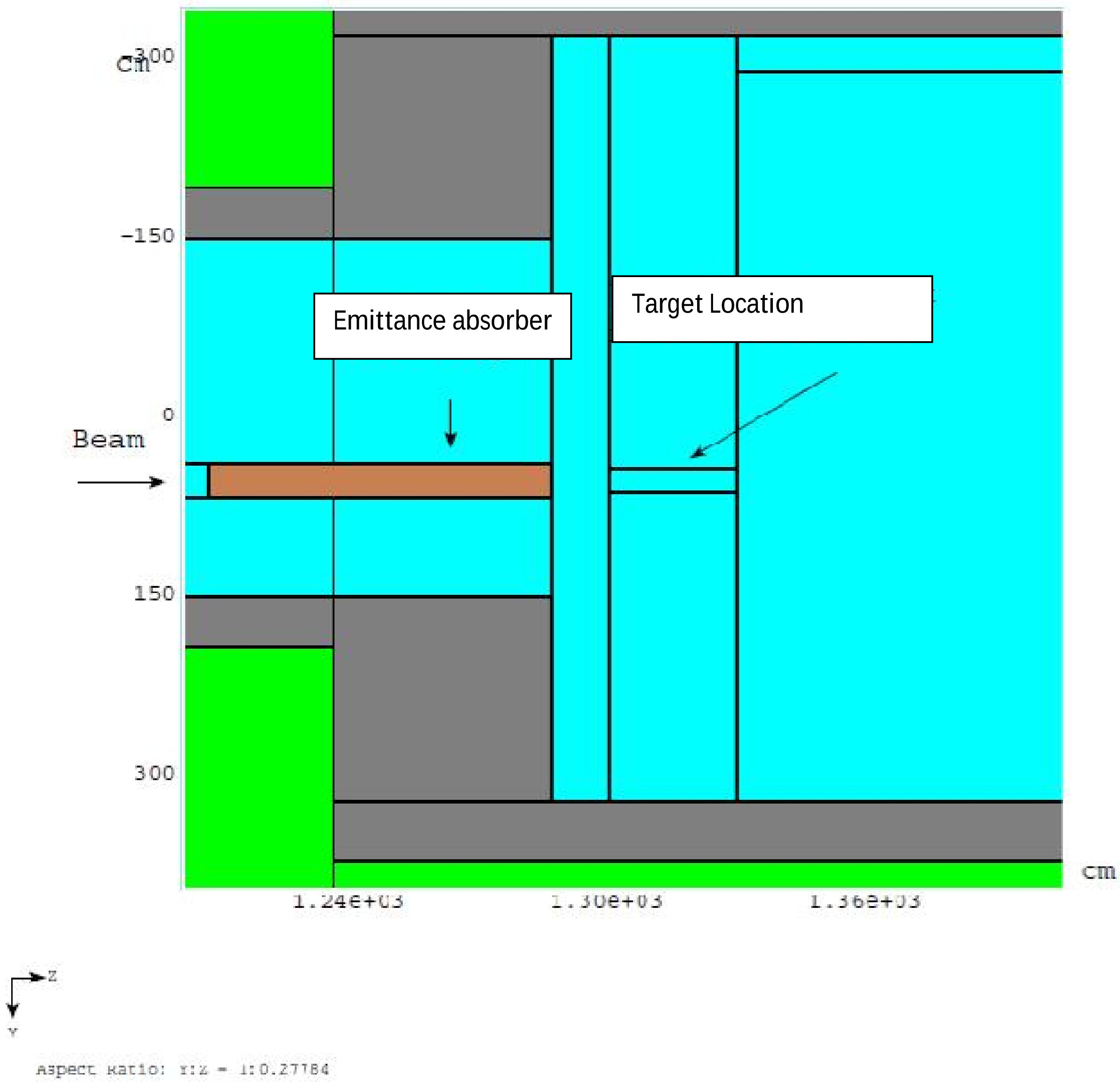


Figure 12: A fragment of the MARS model of MTA (plan view). The emittance absorber is a cylinder 30 cm in diameter and 66 cm in length. The target, a copper cylinder 20 cm in diameter and 30 cm in length (100% interaction length), is not shown in the Figure.

The scenario which produces the largest prompt dose in the refrigerator room is a scenario where a fraction of neutrons, generated by the beam on the thick target experiences small-angle scattering, is transported through the horizontal penetrations to the refrigerator room, and eventually to the parking lot. Results of Monte Carlo modeling are presented in Figs. 13 thru 16. Without any shielding in the MTA target hall the calculated dose at the entrance to the penetration is 53 mrem/pulse. The dose attenuation in the biggest penetration is approximately 7×10^{-4} (see Fig. 13). In Fig. 16 one can see that the calculated dose in the parking lot near the roll-up door is about 3.2×10^{-6} mrem/pulse.

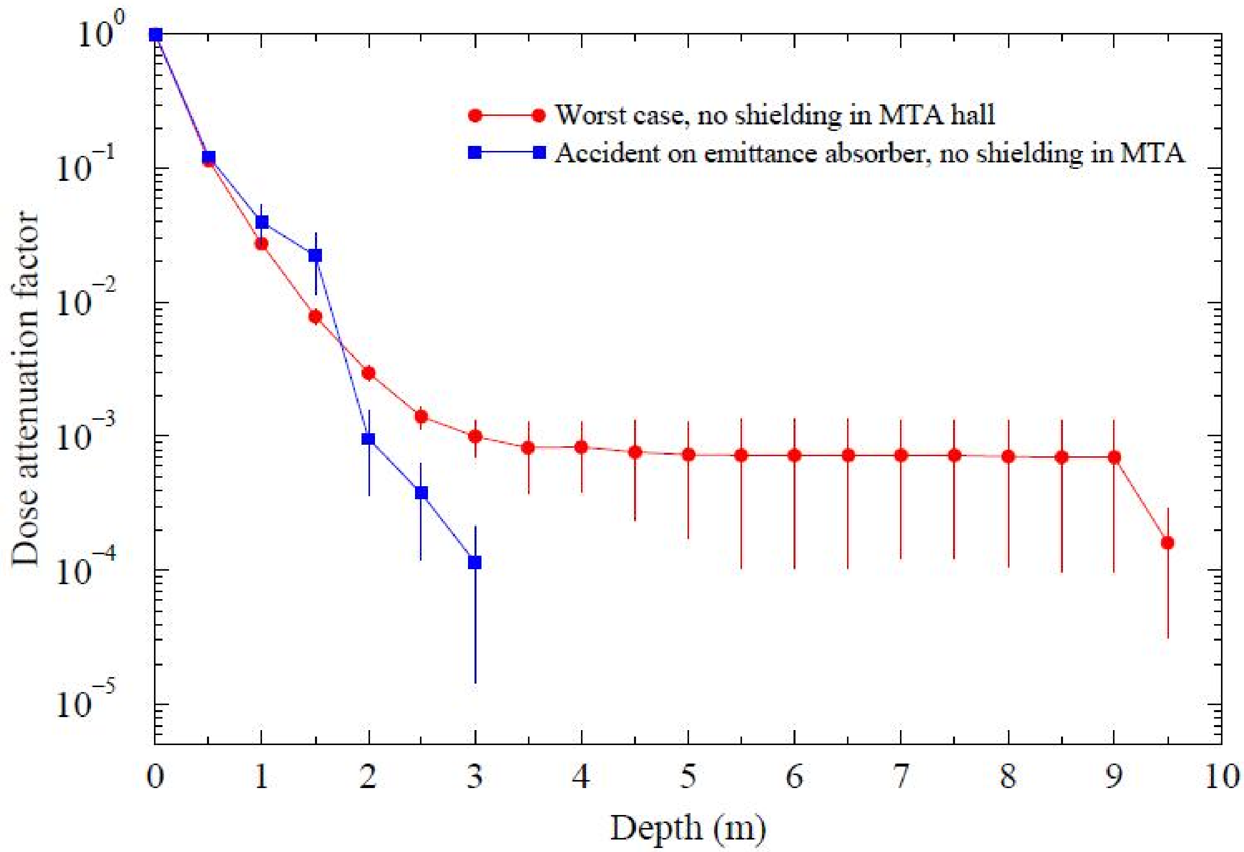
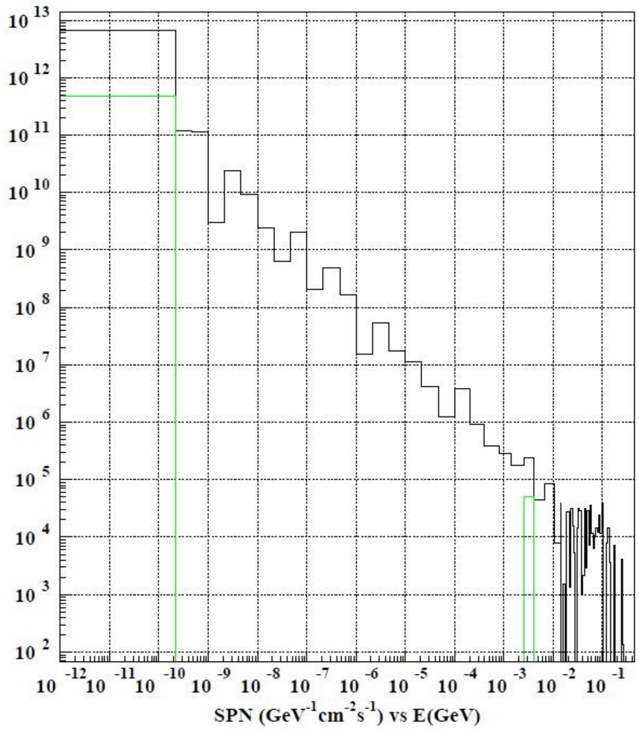


Figure 13: Calculated dose attenuation in the 10” penetration containing the cryogenic channel for the thick target in the experimental hall. Also shown is the dose attenuation for beam deposited on the emittance absorber. The dose at the entrance to the penetration is assumed to be equal to unity. The calculated dose refers to volumes occupied with vacuum in the cryogenic channel.



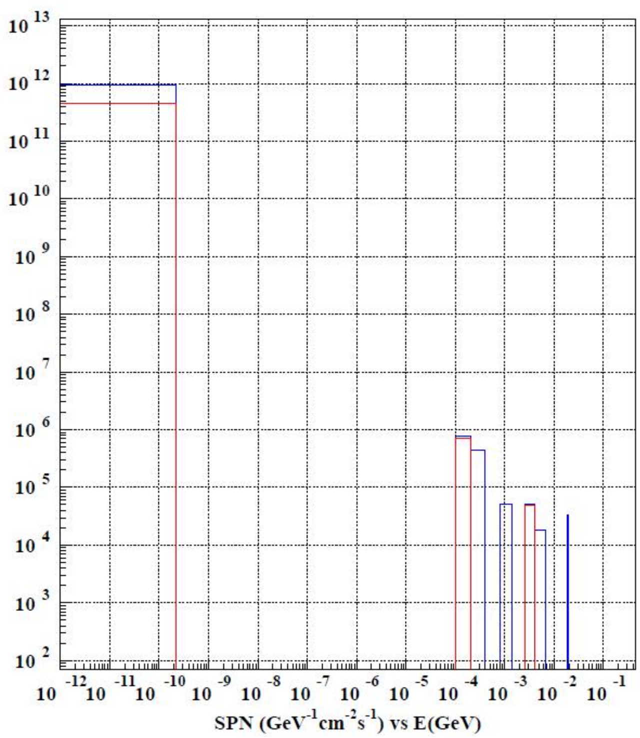


Figure 14: Calculated neutron energy spectra in the 10” penetration containing the cryogenic channel for the thick target in the experimental hall. Normalization of the energy spectra is arbitrary. The calculated spectra refer to volumes occupied with vacuum in the cryogenic channel. The solid black, blue, red and green lines refer to the following depths in the penetration: 0-2, 2-4, 4-6 and 6-8 m, respectively. For the depths 6-8 m about 60% of neutrons have energies from 0.001 eV up to 2 eV and 40% of neutrons have energies from 2.5 up to 4 MeV.

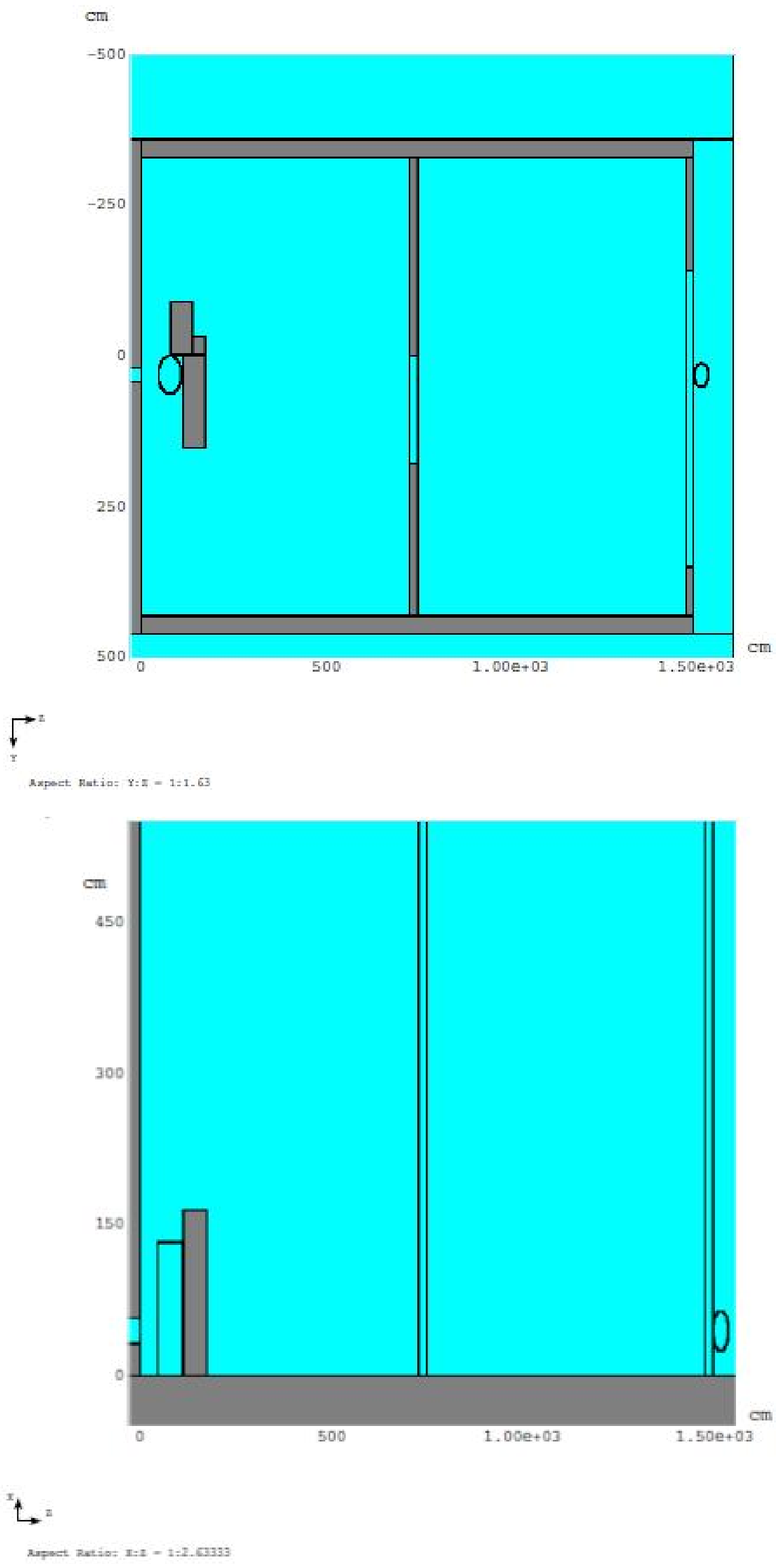


Figure 15: A plan (top) and elevation view (bottom) of the MARS model of the refrigerator room. Several blocks of concrete (60 cm in thickness) in the room serve to shield against radiation emanating from the penetrations.

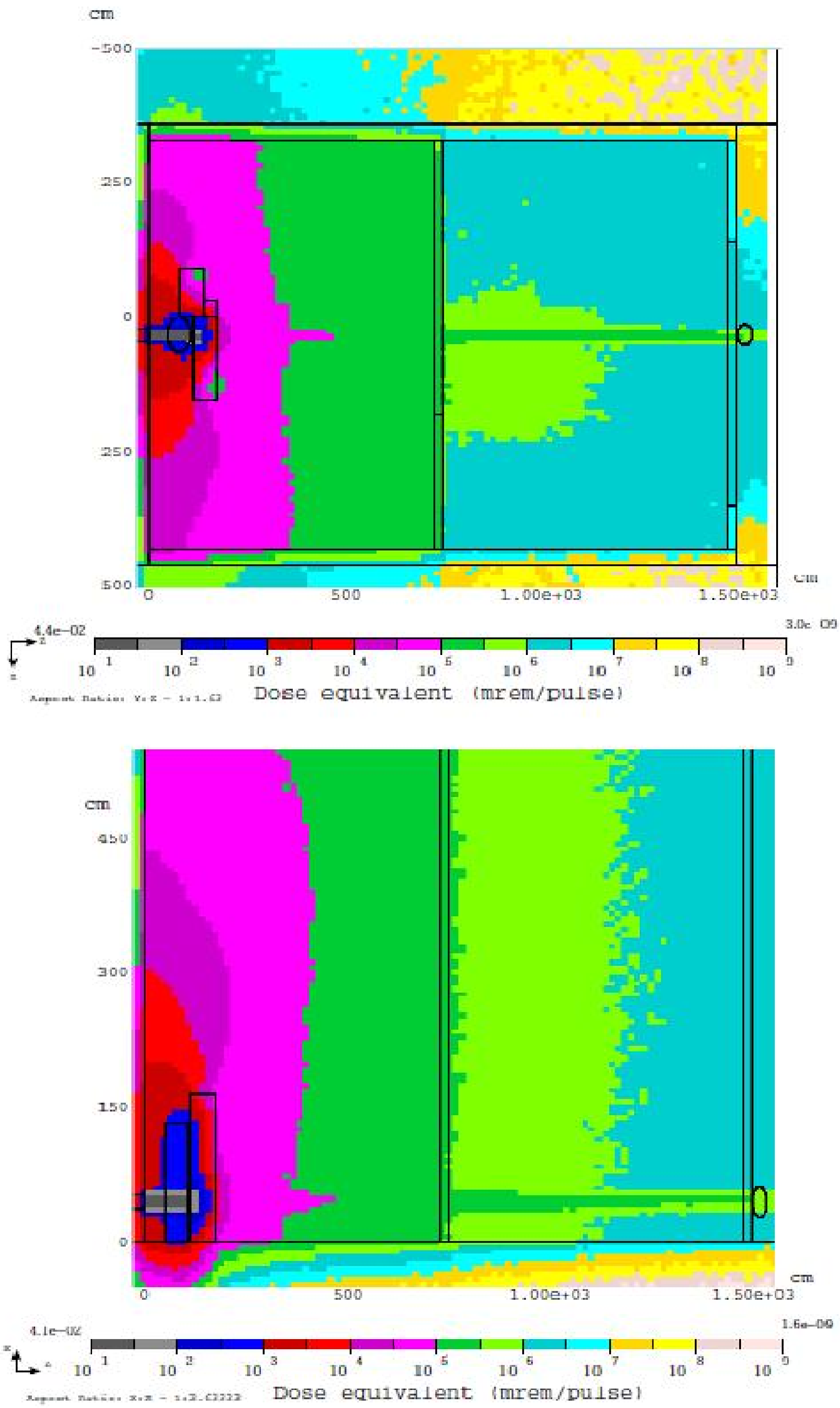


Figure 16: Calculated dose distributions in the refrigerator room for the thick target in the experimental hall: a plan (top) and elevation view (bottom).

The dose at the sides and top of the concrete shield wall in the refrigerator room is worse than the dose on the face of the wall (see Figs. 15 and 16). Therefore, a fence should be put around the concrete shield wall. The calculated maximum dose at the sides and top of the wall is 3×10^{-4} and 6×10^{-4} mrem/pulse, respectively.

For beam deposited on the emittance absorber the calculated dose at the entrance to the 10" penetration is 19 mrem/pulse. A calculated dose attenuation in this case is shown in Fig. 13. One can see that the emittance absorber provides additional scattering and absorption when compared with the 30-cm target. Extension of these results to obtain a dose estimate for all six penetrations is discussed in Reference 3.

References

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N. V. Mokhov, S. I. Striganov, "MARS15 overview," Proc. Hadronic Shower Simulation Workshop, Batavia, Illinois, USA, 6-8 September, 2006, Vol. 896, pp. 50-60, American Institute of Physics, Melville, NY (2007); http://www-ap.fnal.gov/MARS/

[2] I. Rakhno, C. Johnstone, Fermilab-TM-2248 (2004); I. Rakhno, C. Johnstone, Fermilab-TM-2305-AD (2005).

[3] B. Higgins," Summary of Labyrinths and Penetrations in the Muon Test Area (MTA) Enclosure", June 2010.